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A Synopsis of Yaw-Induction Techniques Used During Projectile Free-Flight Aerodynamics Experiments

by Bradford S. Davis and Bernard J. Guidos

ARL-RP-420 **March 2013**

A reprint of the *63rd Aeroballistic Range Association Meeting*, Brussels, Belgium, 1–4 October 2012.

NOTICES

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14. ABSTRACT
Projectile free-flight motion measurement from yaw cards, spark ranges, and instrumented projectiles and accompanying analyses have become integral components of weapon system development. The projectile's aerodynamics can be extracted from these free-flight motion data by fitting to the 6-degree-of-freedom equations of motion. Because many of these aerodynamic coefficients vary as a function of angle of attack, generating a sufficiently large angle of attack and/or a variety of angles of attack is necessary for complete aerodynamic characterization. Achieving this often requires special attention. Over the years, numerous yaw-induction techniques have been developed to deliberately increase the angular disturbances experienced by the projectile during launch. Yaw-induction during free-flight experiments is often necessary for two main reasons: (1) to produce angular motion large enough to diminish the effect of measurement and modeling errors, thereby increasing the accuracy of the fitted data, and (2) to produce a set of shots at varying yaw levels to characterize the nonlinear behavior of aerodynamic coefficients with respect to yaw. This report describes a variety of techniques that have been used to induce free-flight projectile angle of attack during the launch phase, and provides insight pertaining to their implementation and success based upon some quantitative results.

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Summary - Projectile free-flight motion measurement from yaw cards, spark ranges, and instrumented projectiles and accompanying analyses have become integral components of weapon system development. The projectile's aerodynamics can be extracted from these free-flight motion data by fitting to the 6-DOF (degree of freedom) equations of motion. Because many of these aerodynamic coefficients vary as a function of angle of attack, generating a sufficiently large angle of attack and/or a variety of angles of attack is necessary for complete aerodynamic characterization. Achieving this often requires special attention. Over the years, numerous yaw-induction techniques have been developed to deliberately increase the angular disturbances experienced by the projectile during launch. Yaw-induction during free-flight experiments is often necessary for two main reasons: (1) to produce angular motion large enough to diminish the effect of measurement and modeling errors, thereby increasing the accuracy of the fitted data, and (2) to produce a set of shots at varying yaw levels to characterize the nonlinear behavior of aerodynamic coefficients with respect to yaw. This paper describes a variety of techniques that have been used to induce free-flight projectile angle of attack during the launch phase, and provides insight pertaining to their implementation and success based upon some quantitative results.

1. INTRODUCTION

Projectile free-flight motion measurement and accompanying analysis have become integral components of weapon system development. Current in-house ground- and telemetry-based free-flight measurement methodologies used by the U.S. Army Research Laboratory (ARL) were recently reported by Davis et al. [1]. These methodologies include the use of yaw cards, spark ranges, and instrumented projectiles as the main means of gathering the free-flight data. The aerodynamics can then be extracted from the free-flight motion data by fitting to the 6-DOF (degree of freedom) equations of motion [2, 3]. Many of these aerodynamic coefficients vary as a function of Mach number and angle of attack. Controlling the Mach number can be easily done by firing the projectiles at different charge levels to achieve the desired muzzle velocity. However, generating a sufficiently large angle of attack, or a variety of angles of attack, often requires special attention.

The introduction or control of physical processes to intentionally increase a projectile's angle of attack as it enters free-flight is commonly referred to as yaw induction (the term "yaw" is often used interchangeably with "angle of attack"). Yaw induction during free-flight experiments is often necessary for two main reasons: (1) to produce angular motion large enough to diminish the effect of measurement and modeling errors, thereby increasing the accuracy of the fitted data, and (2) to produce a set of shots at varying yaw levels to characterize the nonlinear behavior of aerodynamic coefficients with respect to yaw. Under most circumstances, the naturally occurring launch disturbance is inadequate to impart enough angular motion for accurate determination of all aerodynamic coefficients and derivatives of interest. In order to achieve larger-than-normal yawing motion during the experiments, some method of amplifying the initial angular disturbance as the projectile exits the launch tube is often needed.

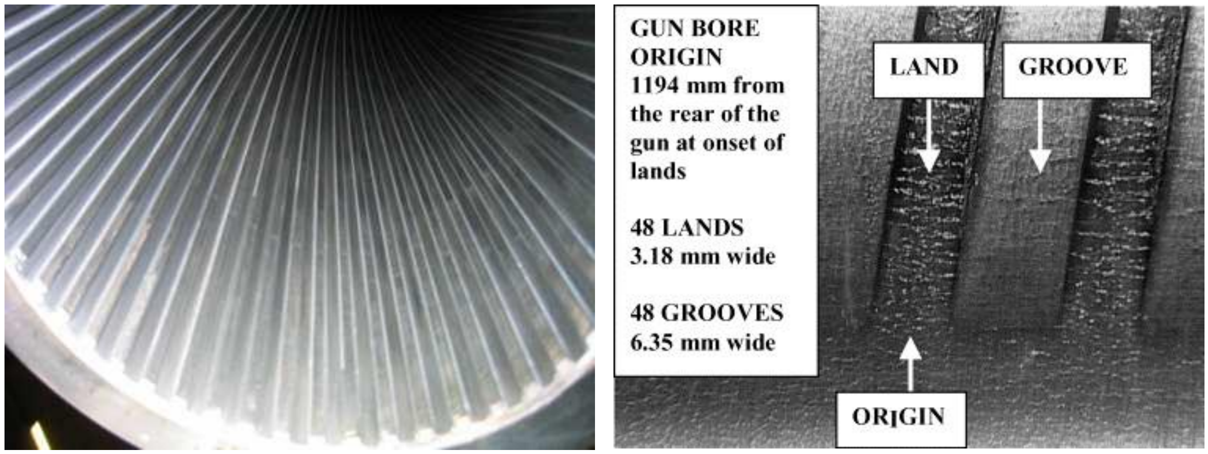
Over the years, numerous yaw-induction techniques have been developed to deliberately increase the angular disturbances experienced by the projectile during launch, thereby inducing larger free-flight yaw levels. The appropriate technique can depend upon many considerations, such as projectile caliber, projectile geometry, amount of yaw required, experimental setup limitations, and launcher/gun motion. In this paper, we describe a variety of techniques that have been used to induce free-flight projectile angle of attack during the launch phase, and provide insight pertaining to their implementation and success based upon some quantitative results.

2. WORN TUBES AS YAW-INDUCERS

Prior to entering free-flight, angular disturbances acting on the projectile generate pitching and yawing motion that produces a corresponding initial maximum angle of attack. The term "tip-off" is often used loosely in conversation to refer to the angular disturbances, the initial angles and angular rates they produce, or the initial maximum angle of attack itself. Larger tip-off implies larger initial maximum angle of attack in free-flight. Whichever usage is employed, the origins of tip-off have been a fundamental topic of interest in aeroballistics [4, 5]. Angular disturbances are predominantly introduced while the projectile is still in bore or in transition (i.e., mechanically disengaged from the gun tube but not yet in free-flight).

Worn gun tubes of fielded large-caliber artillery systems provide a good example of in-bore angular disturbances and their effect on the maximum angle of attack. Launch from worn gun tubes was identified as the leading cause of excessive tip-off for a class of fielded 155-mm artillery projectiles [6, 7]. Gun tubes that have fired hundreds of shots (fewer shots for improperly maintained gun tubes) display signs of erosion in their lands and grooves (figure 1). The resulting pits increase the gaps between the projectile engagement surfaces and the gun bore surface, effectively changing the engagement characteristics. The projectile can become more loose fitting in the tube and/or propellant gases can flow past the projectile (i.e., leakage or, in extreme cases, blow-by). Excessive clearance in a worn tube also allows the projectile to move laterally from its centerline, thus increasing the in-bore balloting (defined here as any transverse or pitching/yawing motion of a projectile in the gun tube) and producing larger tip-off.

New Tube



Worn Tube

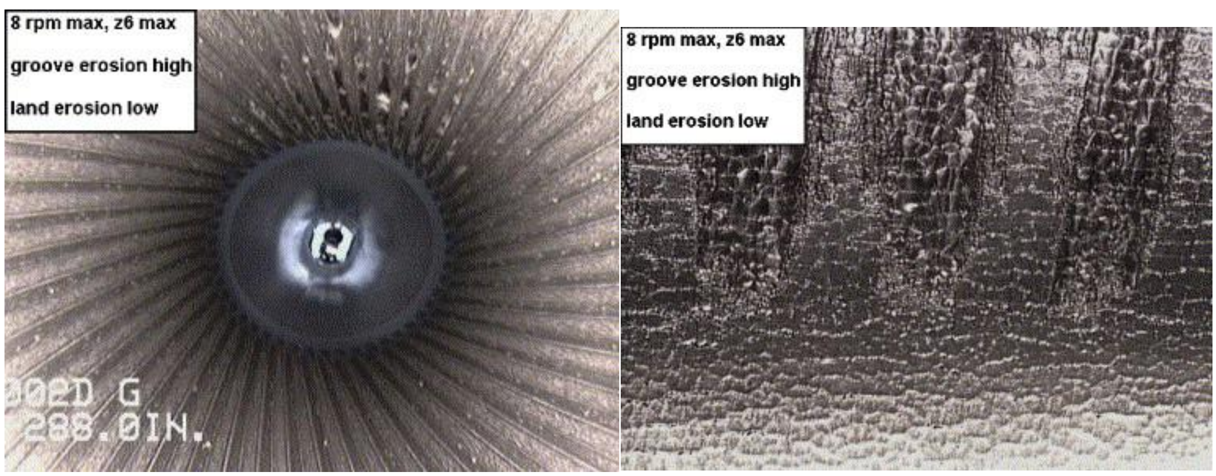


Figure 1. 155-mm gun barrel images showing gun wear.

Figure 2 shows flight data collected during a recent instrumented 155-mm projectile flight launched from a fourth quarter (i.e., highly worn but still serviceable) gun tube. The data represent angular aspect angle of the projectile body relative to the Earth's magnetic field. The maximum angle of attack during the earliest portion of the flight can be approximated as half of the peak-to-peak amplitude of the first full slow-mode yawing cycle. This projectile exhibited a 7.5-degree first maximum angle of attack, which is three-to-four times larger than the typical maximum angle of attack when launched from a new or slightly worn gun tube.

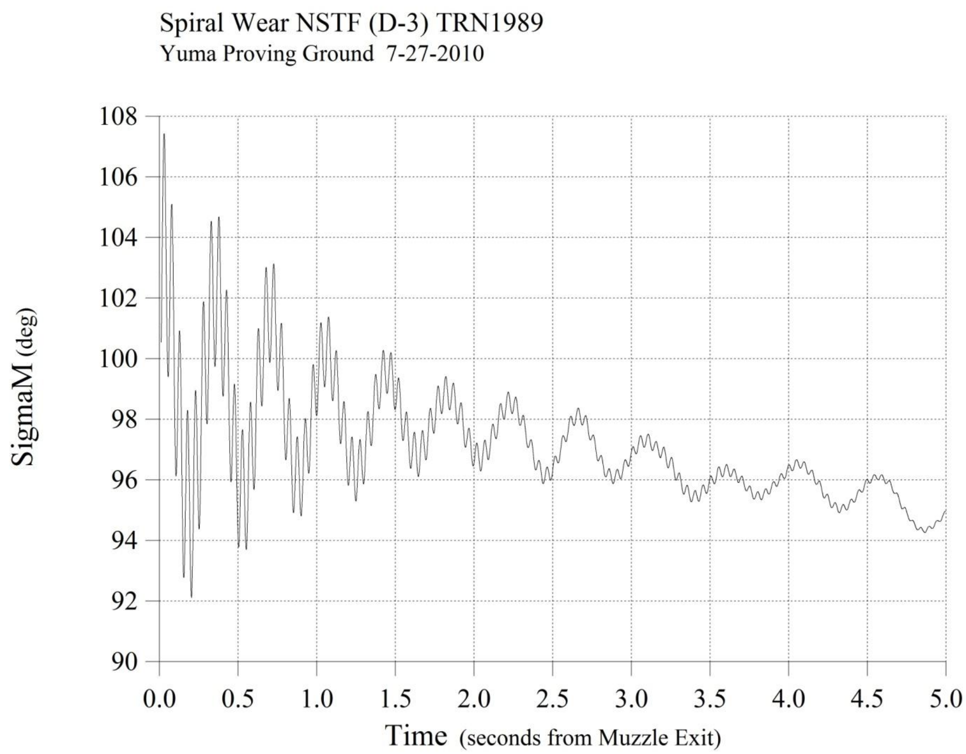


Figure 2. Flight motion produced from a worn artillery gun tube with a 7.5-degree first maximum angle of attack.

Launch from a worn gun tube can, in effect, serve as a simple and passive technique for inducing large free-flight projectile angle of attack. Ironically, the most challenging aspect of this approach may be the materiel requirements of quantifying, labeling, and storing non-serviceable gun tubes. Without this special attention, such gun tubes would naturally be associated with an end-of-life-cycle process intended to prevent their inadvertent use. Moreover, the practicality of retaining worn gun tubes to produce a variety of angles of attack at all calibers of interest can be rather limited.

3. SHOOTING THROUGH HIGH DENSITY GAS TO INDUCE YAW

Cobb [8] and Winchenbach [9] describe a yaw-induction technique developed for 20-mm spin-stabilized projectiles fired through the indoor spark range located at Eglin Air Force Base (EAFB), FL. This method exploited the projectile's gyroscopic stability characteristics as a means of achieving an initial angular disturbance without imparting a corresponding transverse velocity. This was accomplished by flying the projectile through a 3-m-long, 10.2-cm-diameter tube containing a high-density refrigerant gas (figure 3). The tube was sealed at both ends with diaphragms, the air pumped out, and a sufficient amount of high density gas pumped into the evacuated tube. Once the projectile punctured the diaphragm and entered the tube, the angular motion increased because it was gyroscopically unstable in the denser medium. Upon exit from the tube, the augmented angular motion was measured and analyzed.

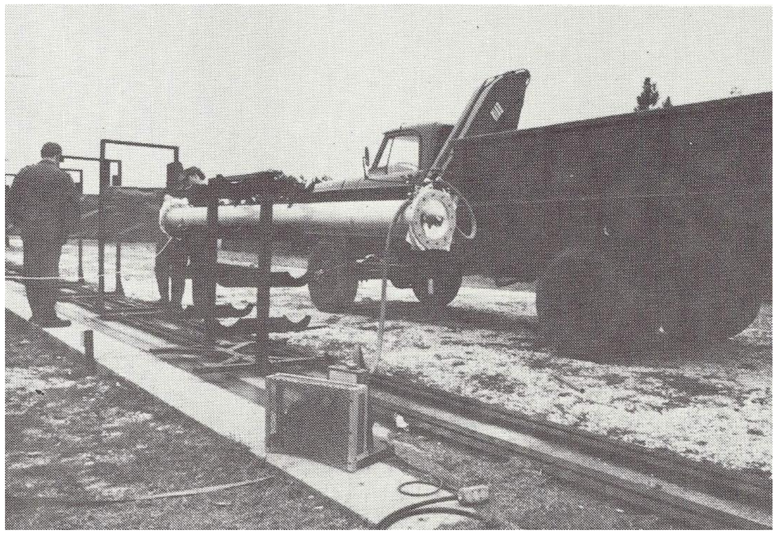


Figure 3. High-density gas holding tube used at EAFB.

Figure 4 shows the first maximum angle of attack for shots having launch Mach numbers varying from 1.6 to 3.1, plotted as a function of gas mass in the tube, with tube standoff distance as an additional parameter. The technique produced first maximum angles of attack (that is, downrange of the gas tube) as large as 53 degrees. Shots that did not use this technique (not included in the plot) had first maximum angles of attack that varied from a few degrees to 10 degrees. Gates et al. [10] used this technique to produce first maximum angles of attack of as much as 45 degrees, depending on the Mach number, amount of high-density gas, and tube distance from the muzzle. With today's environmental safety concerns, the use of refrigerant as the high-density gas is effectively prohibited. Environmentally approved high-density gases may be available, but a search was not undertaken for the purposes of this paper.

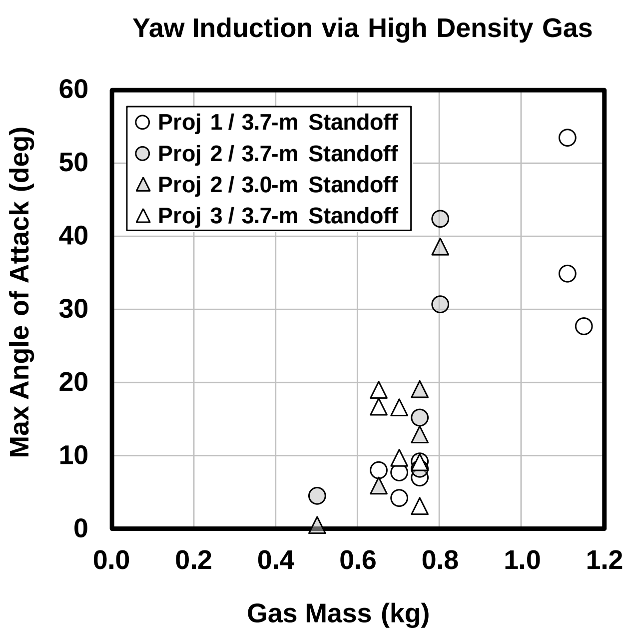
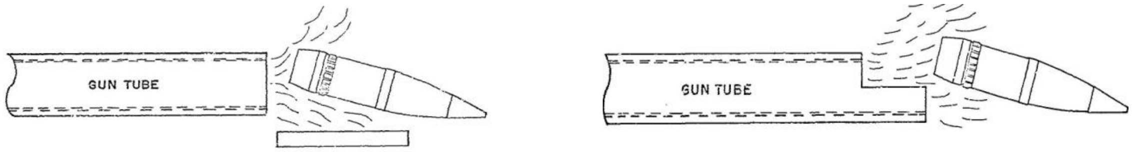


Figure 4. Effect of high-density gas on first maximum angle of attack.

4. ASYMMETRIC MUZZLE BLAST LOADING

One of the most extensively used yaw-induction techniques is to create a region near the muzzle in which the applied loads on the projectile are asymmetric. In 1972, Boyer [11], from the Ballistics Research Laboratory (BRL), reported on two yaw-induction techniques employed for artillery firings using asymmetric muzzle blast loading. The first was the flat plate technique, executed by firing past a rigidly held flat plate located on one side of the muzzle (see figure 5a). Its effectiveness depended on positioning the plate close enough to get the desired effect without being hit by the projectile. Another difficulty with the flat plate technique is setting up such a system for a program requiring high gun elevation angles and multiple gun angles. Boyer [11] also described a second asymmetric technique that consisted of cutting away a small section of the gun tube muzzle (see figure 5b). This method was not always practical because it would ruin the tube for any other use.



a) Flat plate technique b) Notched tube technique

Figure 5. Asymmetric loading techniques employed by Boyer.

In the late 1970s, improved asymmetric muzzle blast generation techniques were developed at BRL that do not damage the tube and allow for arbitrary gun aiming by modifying actual muzzle brakes attached to the gun tube. Several researchers had used this technique, but it was first described in detail in 1989 by Pennekamp [12]. This configuration induces yaw by creating an asymmetric flow field for the gun gases, resulting in a pressure load concentrated on one side of the projectile (see figure 6).

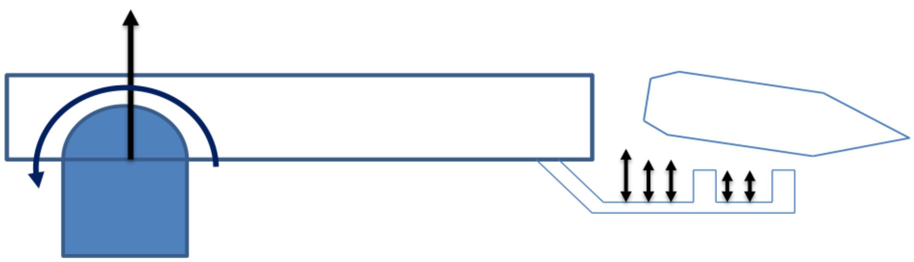


Figure 6. Depiction of modified muzzle-brake yaw-induction system and resulting moment.

Modifying a muzzle brake to produce asymmetric blast loading can be highly effective; so effective, in fact, that it can introduce two concerns not present with Boyer's techniques. First, because sizable trajectory deflections can result from the greater magnitude asymmetric blast loads that can be induced with modified muzzle brakes, safety concerns can arise for people and instrumentation during indoor firings, such as through a spark range. Outdoor firings, such as elevated telemetry experiments, can be conducted with less risk of damage to instrumentation due to less constrained spatial considerations and use of armor-like shielding.

Second, because the modified muzzle brake is attached to the gun (unlike the flat plate), the asymmetric blast load also acts on the gun, imparting a larger force and a moment that do not occur under normal operating conditions. These additional loads are transferred to the gun mount and recoil system, which can be damaged if the loads are large enough. Therefore, care must be taken when using this method to limit the launch velocities so the force and torque imparted by the asymmetric blast loading are within the capabilities of the mount and/or recoil system.

4.1 155-mm Modified Muzzle Brakes

In this section, several examples of yaw induction via asymmetric muzzle-blast loading are presented. Experiments reported by D'Amico et al. [13] and Loeb [14] are examples of yaw induction using modified large-caliber muzzle brakes, achieving initial maximum angle of attack as large as 9 degrees. More recently, Davis et al. [2] used a muzzle brake that had been cut in half to create muzzle tip-off; full-length side plates covering both baffles were welded to the brake (see figure 7). In these experiments, angular measurements were obtained from onboard sensors whose output were telemetered and recorded for post-flight processing.

Figure 7. 155-mm half-muzzle brake with full side plates.

Figure 8 shows a frame from a high-speed video of a 155-mm gun firing through the half-brake with full side plates. The image shows the asymmetrical nature of the flow, with expelled gas forced upward after imparting an upward force on the projectile aft end and producing a nose-downward initial projectile motion. Figure 9 shows the projectile angle of attack (alpha) history resulting from this firing. In this instance, a first maximum yaw level of approximately 15 degrees was attained using the half-brake with full side plates.

Figure 8. 155-mm gun firing using half-brake with full side plates.

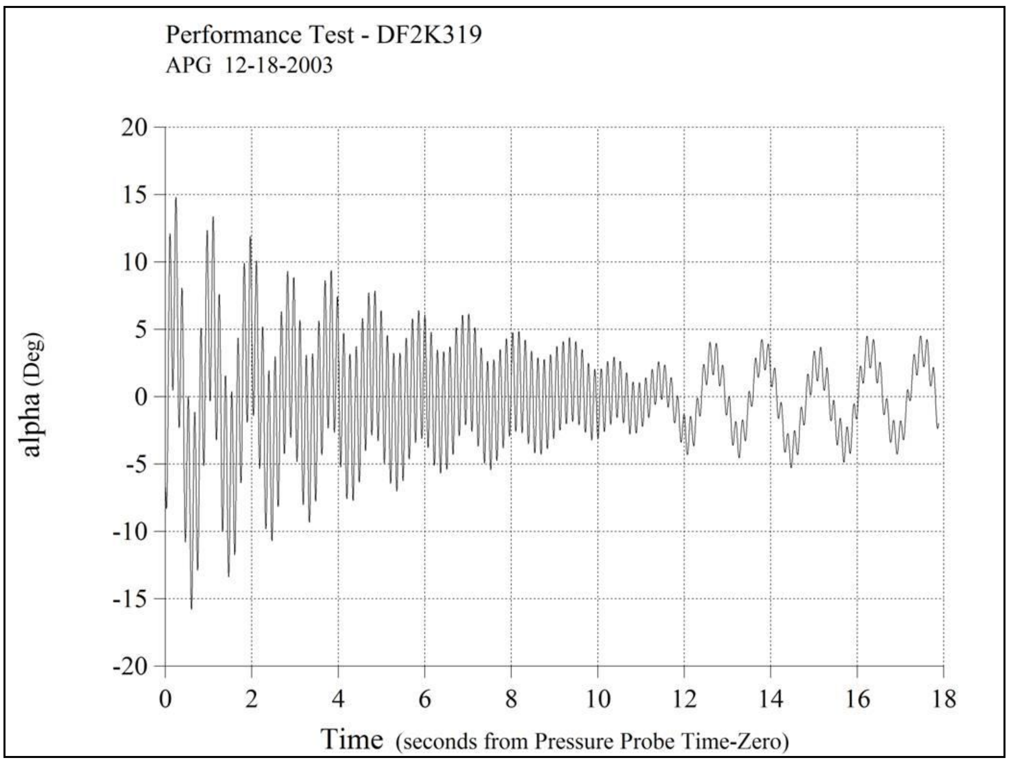


Figure 9. Flight motion from a 155-mm projectile from a gun tube with half-muzzle brake.

Several variations of modified 155-mm brakes have also been utilized with the M284 gun system by the U.S. Army Armament Research Development and Engineering Center (ARDEC) during experiments at Yuma Proving Ground, AZ. Figure 10a shows a half-brake with half plates, which is a full muzzle brake cut in half with side plates welded to the first baffle only. Figure 10b shows a quarter-brake, which is a half-brake cut again to remove its second baffle and with no side plates. These two additional asymmetric muzzle brakes produced small-to-moderate first maximum angles of attack. This translated into about 5–6 degrees maximum angles of attack for the half-brake and 2–3 degrees maximum angle of attack for the quarter-brake.

a) Half-muzzle brake with half plate. b) Quarter-muzzle brake.

Figure 10. 155-mm cannon modified muzzle brakes for yaw induction.

ARL recently reanalyzed a set of 155-mm artillery projectile spark-range firings that had been conducted using an M185 gun tube muzzle brake modified into a half-brake. The field notes from the firings did not specify if side plates were used, and no photographs of the gun were available. The modified brake was used for firings with launch Mach numbers as large as 1.1. Figure 11 shows the first maximum angles of attack ($\overline{\alpha}_{max}$) for 17 shots, 6 of which were conducted using the half-brake (shown as solid circles). Generally, but not always, the half-brake induced larger first maximum angles of attack compared to shots conducted with a full muzzle brake.

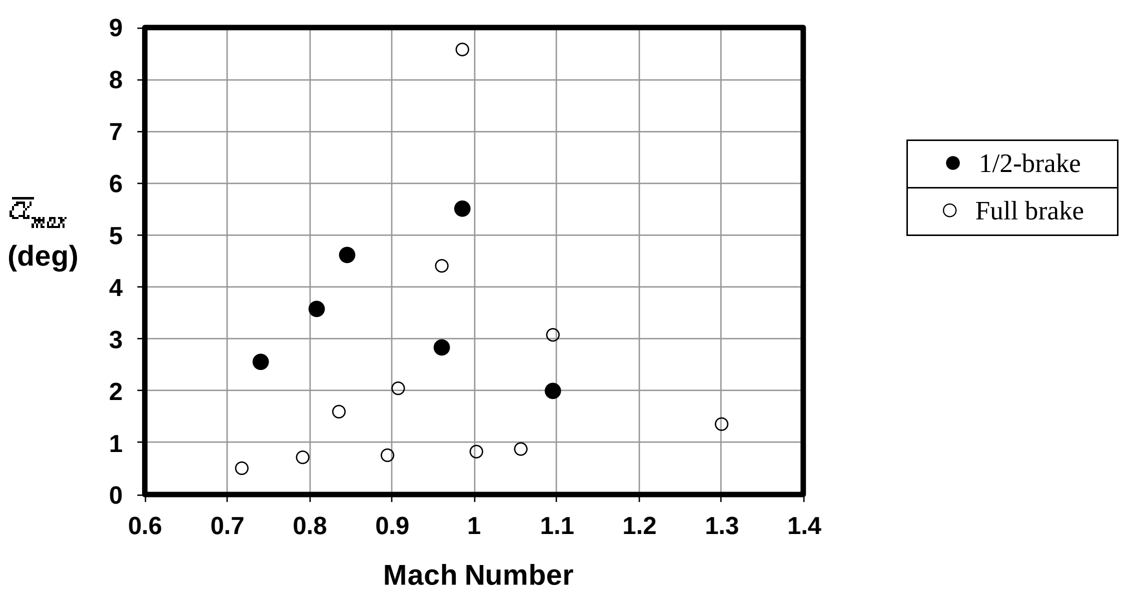
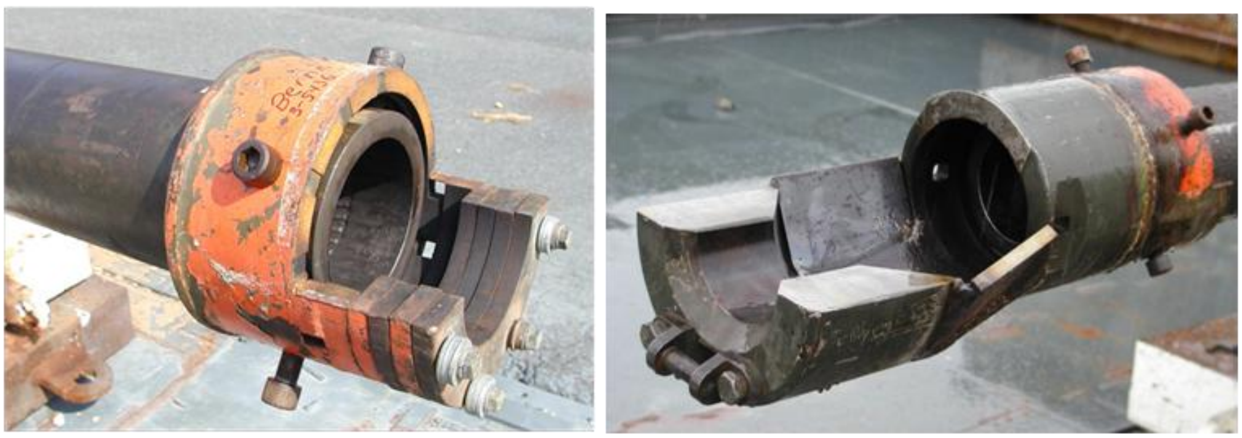


Figure 11. 155-mm firings showing effect of half-muzzle brake yaw-inducer.

4.2 105-mm Modified Muzzle Brakes and Fabricated Muzzle Devices

Modified muzzle brakes and fabricated muzzle devices have also been used with varying success for 105-mm artillery systems. One such program was recently conducted at ARL firing an M137E1 cannon from an M102 howitzer and M37 recoil mechanism. A previously fabricated M137-compatible yaw-inducer, shown in figure 12a, was used at the onset of the firings. The length of this yaw-inducer could be changed by adding or removing front plates to affect the muzzle blast flow. In order to induce even more yaw, a half-brake with welded side plates from an M20A1 cannon was adapted for use on the M137 cannon, as shown in Figure 12b. Because the inside diameter (ID) of a M20A1 muzzle brake is larger than the outside diameter of the M137, the M20A1-compatible half-brake was welded to an M137-compatible yaw-inducer that clamps to the M137E1 muzzle with four bolts. The device could be attached at a specified location relative to the muzzle in order to vary the interaction between the asymmetric blast flow and the projectile aft end.



a) Fabricated M137-compatible yaw-inducer.   b) Modified M20A1 cannon half-brake.

Figure 12. 105-mm cannon yaw-inducing devices.

Another 105-mm program, conducted by ARDEC, used the same 105-mm half-brake configuration, with and without side plates, for firings from an M20A1 gun tube in the M119A2 howitzer. Figure 13 shows the half-brake without side plates welded to the baffle, and figure 14 shows the half-brake with side plates.

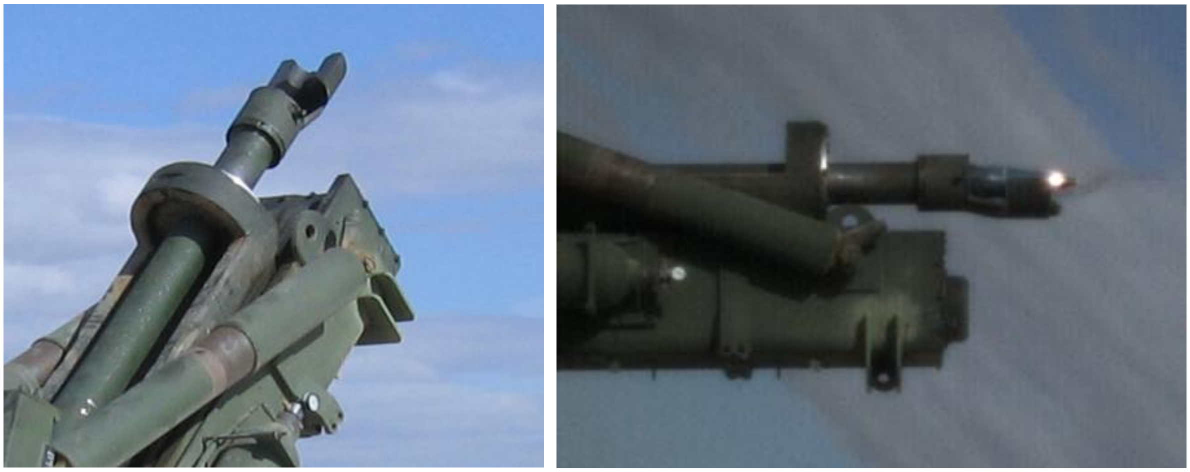


Figure 13. 105-mm half-muzzle brake yaw-inducer.

Figure 14. 105-mm half-muzzle brake with side plates yaw-inducer.

Figure 15 shows the maximum angles of attack achieved for both of the aforementioned 105-mm firing programs. The projectiles differed between the two firing programs, but their geometries were, for practical purposes, somewhat standard for this class of munition. The fabricated M137-compatible yaw-inducer produced maximum angles of attack that were less than desired, and was subsequently abandoned. The half-muzzle brake provided first maximum angles of attack of approximately 4–6 degrees. The half-muzzle brake with side plates provided first maximum angles of attack that varied from almost 6 degrees to more than 12 degrees.

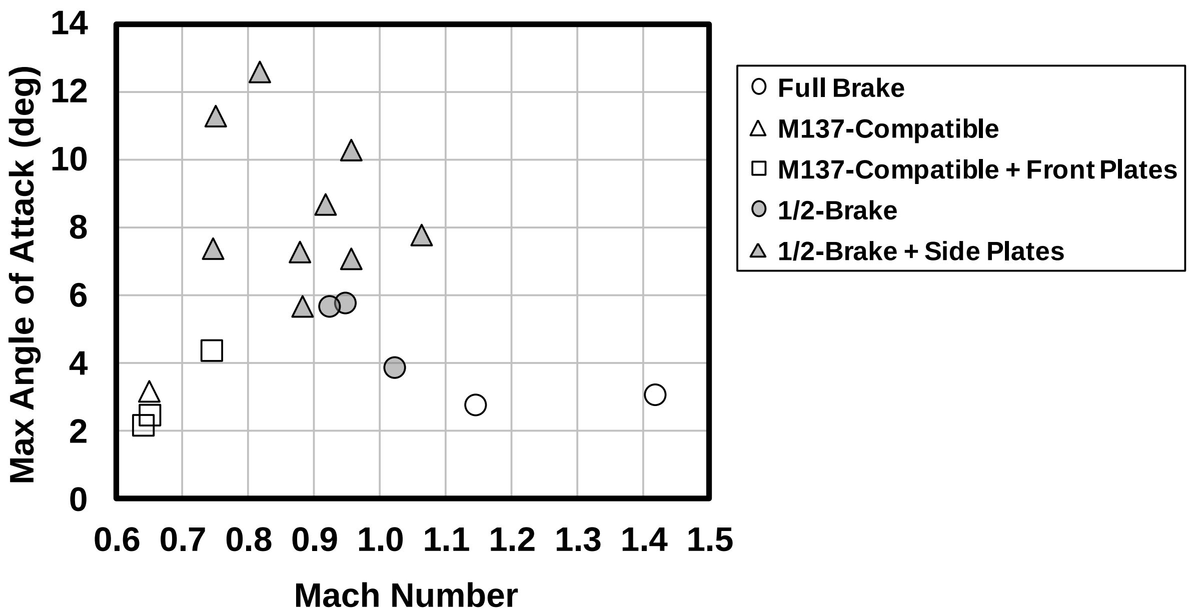


Figure 15. 105-mm projectile maximum angle of attack using with various muzzle devices.

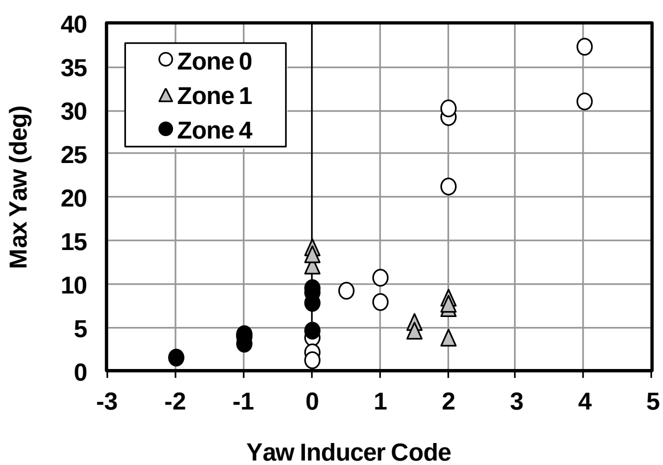
4.3 120-mm Mortar Fabricated Device

A recent 120-mm mortar spark-range program was conducted by ARL using a fabricated asymmetric muzzle blast device similar to the M137-compatible yaw-inducer used in the 105-mm effort previously discussed. The mortar tube was mounted to an M110 vehicle using a custom-made attachment sleigh. Similar to the 105-mm device, a half-moon-shaped device was attached to the end of the gun tube with four bolts, as originally reported by Brown and McCoy [15]. A choice of semicircular plates having the same ID as the muzzle device were used to vary the standoff (i.e., the distance from the muzzle device opening to the muzzle device lip). The device is shown in figure 16, illustrating the approximately 1.5-inch-thick lip attached using five bolts. This particular configuration, with the muzzle device opening positioned near the muzzle itself, shows the 0.33-caliber standoff and is referred to as Yaw-Inducer ID 0.5. Several different standoffs were used during the firings, the largest being 1 caliber, achieved by positioning the entire muzzle device farther out on the gun tube.

This particular launch setup had the launch tube positioned parallel to, and approximately 3 calibers above, the M110 vehicle deck. As such, the muzzle blast may have reflected off the vehicle deck during the firings and affected the projectile's initial angular motion, especially when no muzzle device was used. An additional yaw-inducing mechanism was included in the firings: two 5-inch-long, 0.5-inch-wide, 1.5-inch-tall steel bars welded at right angles to each other onto a plate bolted to the vehicle deck. The welded ends of the two bars were oriented downrange, forming a shallow channel to focus the muzzle blast as it reflected off the plate. This configuration was referred to as a V-Plate. The base plate was bolted onto the vehicle deck at two locations near the muzzle, one approximately a projectile length downrange and the other other approximately two projectile lengths downrange.

Figure 16. Half-moon yaw-inducer for 120-mm mortar (Yaw-Inducer ID 0.5).

The induced maximum yaw levels, shown in figure 17, were found to be highly sensitive to launch velocity (i.e., Zone 0 being the lowest propelling charge and Zone 4 being the highest) and yaw-inducer configuration. The largest angles of attack (greater than 30 degrees) were achieved at Zone 0 using the half-moon with the lip standoff of 1 caliber (Yaw-Inducer ID 4). Interestingly, Yaw-Inducer ID 2 increased the yaw for Zone 0 but decreased the yaw for Zone 1 compared with the bare muzzle firings. The V-Plate configurations (Yaw-Inducers ID 1 and 2) reduced the yaw levels for Zone 4 compared with the bare muzzle firings. The set of firings demonstrated that yaw-inducers can produce vastly different and unexpected trends for different launch conditions. The trends can be largely affected by the details of the muzzle blast propagation and reflection characteristics that demand attention be focused on calibration.



Yaw Inducer ID	Description
0	Bare Muzzle
-2	Bare Muzzle + V-Plate at 1 Projectile Length
-1	Bare Muzzle + V-Plate at 2 Projectile Lengths
0.5	0.33 Caliber Standoff
1	0.5 Caliber Standoff
1.5	0.6 Caliber Standoff
2	0.8 Caliber Standoff
4	1 Caliber Standoff

Figure 17. 120-mm mortar maximum angles of attack using various yaw-inducer settings.

4.4 40-mm Grenade Launcher

A different half-moon yaw-induction technique was developed at ARL for the 40-mm M203 grenade launcher firing full-caliber cartridge projectiles. This technique was first demonstrated using the muzzle-mounted plastic prototype fixture shown in figure 18. One or more thin, circular pieces of Mylar plastic are clasped within the fixture. The outermost band of the projectile impacts the edge of the Mylar, and a nose-downward pitching rate is induced. The plastic prototype fixture was eventually replaced by an aluminum version for the bulk of the firings. The maximum yaw data for five different inducer configurations is shown in figure 19.

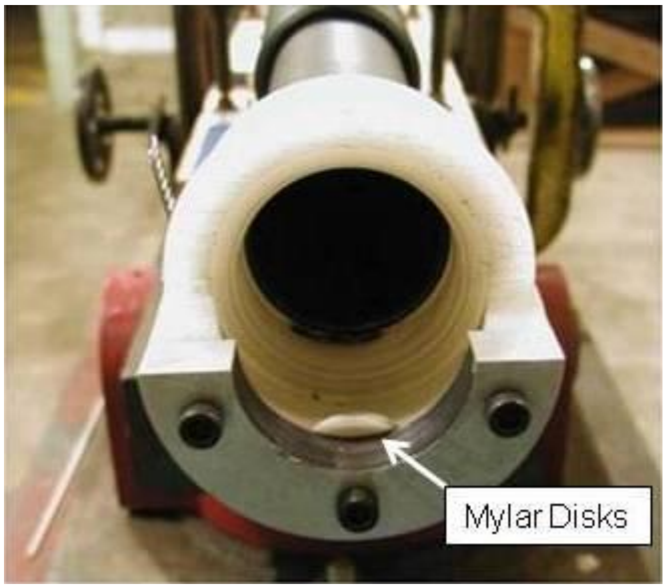
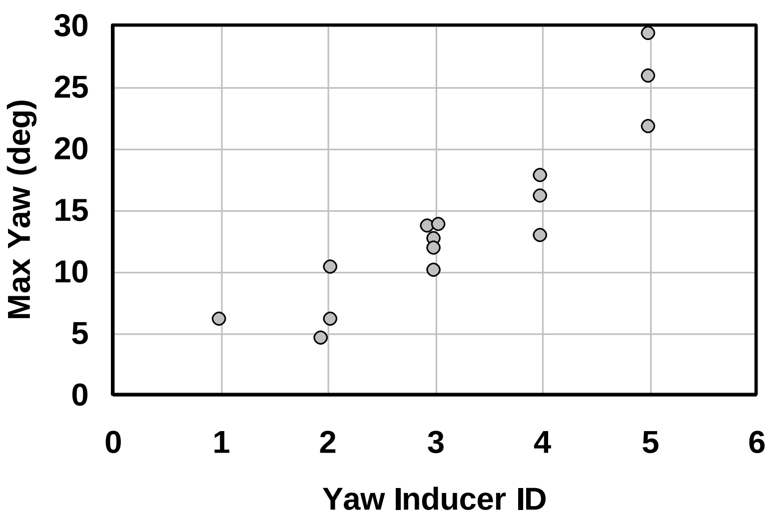


Figure 18. 40-mm M203 launcher yaw-inducer fixture with Mylar deflecting disks.



Yaw Inducer ID	Mylar Disk Configuration Description
1	1 disc; 7/8 in OD; 1/4 in ID
2	2 discs; 7/8 in OD; 3/16 in ID
3	3 discs; 7/8 in OD; 3/16 - 1/4 in ID
4	half-moon 1-piece
5	half-moon 2-piece

Figure 19. First maximum yaw vs. yaw-inducer ID at Mach 0.22.

4.5 5.56-mm Muzzle Device

Yaw-inducers that impart asymmetric loads on the exiting projectile have been used on small-caliber projectiles as well. During flight experiments of 5.56-mm projectiles conducted by McCoy [16], a half-moon yaw-inducer similar in design to those shown in figures 12a and 15 was made from steel and attached to the muzzle via set screws (see figure 20). The length of the asymmetric portion of the device was adjusted by attaching various thicknesses of semicircular discs to the face via cap screws thus varying the impulse delivered to the projectile. The technique was used for firings conducted at Mach 0.7 and 1.1, which were two of the several Mach numbers reported in the study. Maximum angles of attack on the order of several degrees were achieved for a few shots. The report did not specify which shots were conducted using the half-moon yaw-inducer, so no further insight can be gleaned directly from the report.

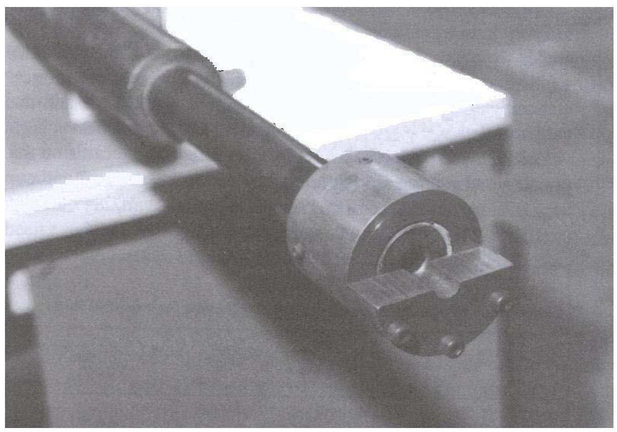


Figure 20. 5.56-mm half-moon yaw-inducing device.

More recently, Howell and Silton (17) reported results from 5.56-mm projectile firings. Preliminary firings from that study were conducted using the same half-moon yaw-inducer hardware that was used for the firings conducted by McCoy (16). It was observed that the half-moon yaw-inducer provided maximum angles of attack of several degrees or more, but the technique lacked round-to-round consistency. As an alternative to the half-moon yaw-inducer, a deflection technique was developed and used for the remainder of the firings, as discussed in the following section.

5. DEFLECTION TECHNIQUES

5.1 5.56-mm Deflection Technique

Boyer [11] was first to report a deflection technique for artillery projectiles called “bouncing” (see figure 21). This involved firing the projectile so that it grazed an object, e.g., a plastic bar located in front of the gun, thereby creating a deflection. This technique worked, but was difficult to calibrate and could cause damage to the projectile.

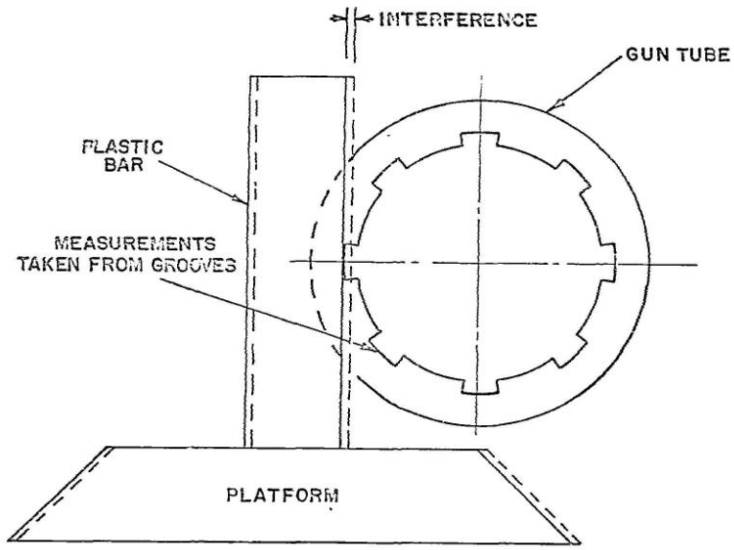


Figure 21. Diagram of bouncing yaw-induction technique.

More recently, deflection techniques using penetration through angled media near the muzzle have been developed. The media consist of materials that can produce an angular disturbance during penetration without damaging the projectile. Howell and Silton (17) reported 5.56-mm projectile firings with yaw induction provided by one or more layers of thick cardboard supported by wooden frames with variable tilt angles and interframe spacing (figure 22). Cardboard tilted at 45 degrees and spaced 1 inch apart provided more consistent yaw induction than the half-moon devices described in the previous section. Figure 23 shows shots with and without yaw induction at three different launch Mach numbers. A maximum angle of attack of 15 degrees was achieved. The number of cardboard layers needed to achieve several degrees angle of attack was somewhat dependent on the Mach number.

Figure 22. 5.56-mm deflection yaw-induction technique.

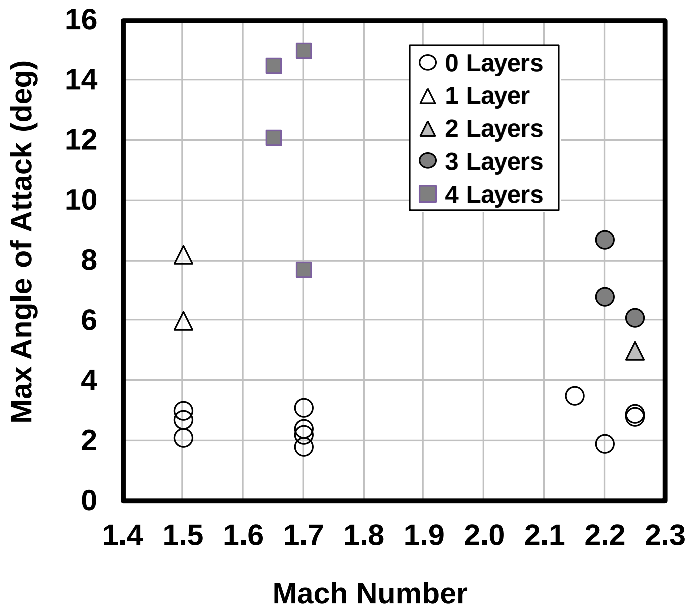


Figure 23. 5.56-mm projectile maximum angle of attack using cardboard deflection technique.

5.2 40-mm Deflection Technique

A similar deflection technique using tilted heavy cardboard was used for a 40-mm spin-stabilized grenade projectile program performed at ARL. After exiting the launcher (seen on the left side of figure 24a), the projectile passes through the cardboard plates before entering the spark range (behind the portal in the wall at the right side of figure 24b). The yaw-induction device was constructed so the number of cardboard deflectors could be varied. Figure 25 shows the first maximum angle of attack as a function of the number of cardboard deflectors for three different Mach numbers.

a) 40-mm launcher and deflector array. b) Closeup of deflector array and range entryway.

Figure 24. 40-mm deflection yaw-induction technique.

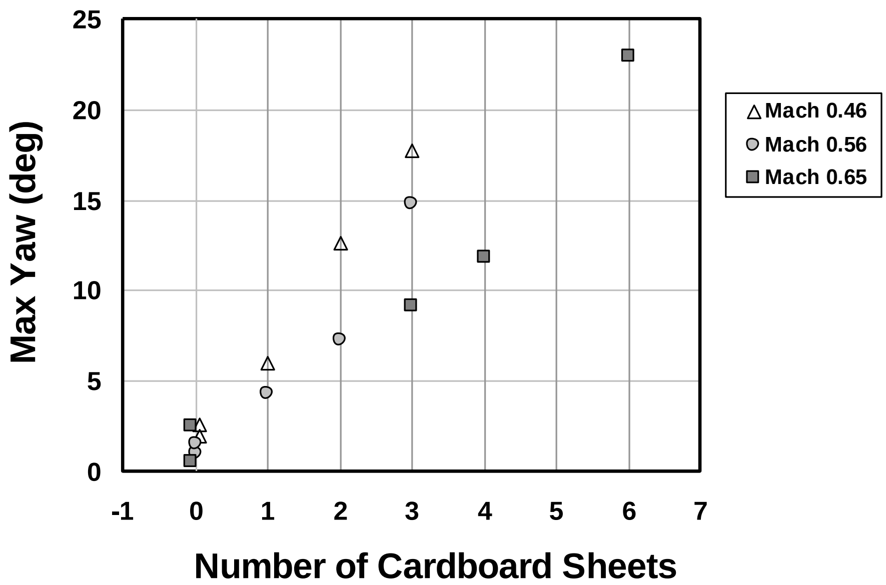


Figure 25. 40-mm first maximum yaw vs. number of sheets.

6. TECHNIQUES USING SUBCALIBER PROJECTILES WITH SABOTS

6.1 Asymmetrical Sabots

With subcaliber projectiles, the gun tube diameter is larger than the projectile diameter and a sabot is required. Coates and Edmanson [18] developed and patented a yaw-inducing technique by making the sabot petals of different lengths and with scooped-out designs on the face. The asymmetric sabot design produced an asymmetric sabot discard that induced yaw to the projectile. They were able to show a correlation between the ratio of the long and short sabot petal lengths and the total yaw induced at launch, as seen in figure 26. Desired yaw magnitudes can then be achieved with appropriate petal length ratios.

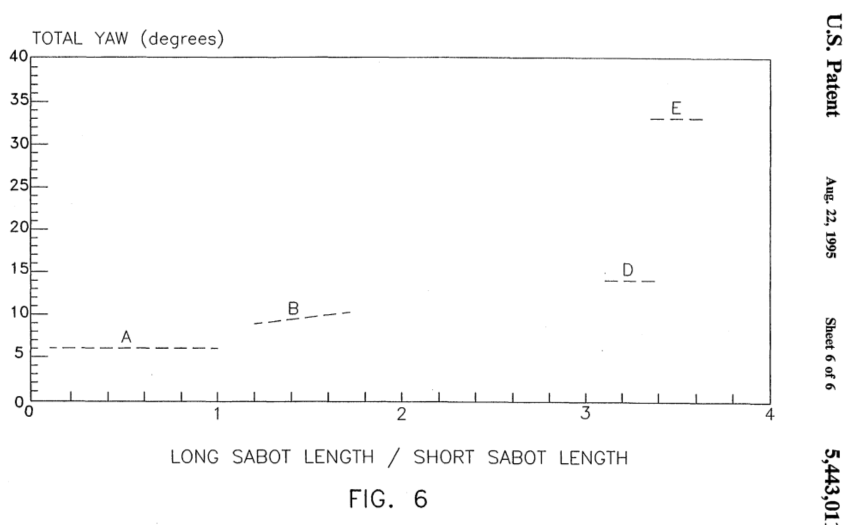


Figure 26. Total yaw as a function of sabot length mismatch.

6.2 Pre-Angled Bodies within the Sabot

Yaw induction of subcaliber projectiles can also be achieved by installing the model within the sabot at a predetermined angle. This was done with National Air and Space Administration crew exploration models during free-flight experiments at ARL, as reported by Topper, et al. [19]. A model pre-angled at 15 degrees within the sabot launch package, shown in figure 27, provided a large angle of attack at sabot discard shortly after launch, as shown in figure 28. This initial angle of attack of approximately 15 degrees initiated a yawing motion that grew in amplitude throughout the ensuing free-flight of the model, and reached an angle of attack of approximately 60 degrees at about 1.5 seconds, as shown in figure 29.

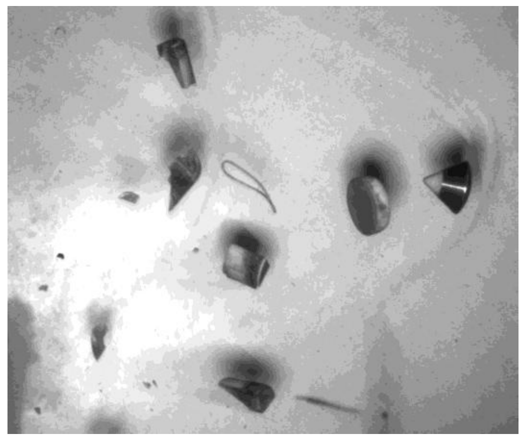


Figure 27. NASA model tilted 15-degree frame within sabot.

Figure 28. Post-launch high-speed video shortly after launch.

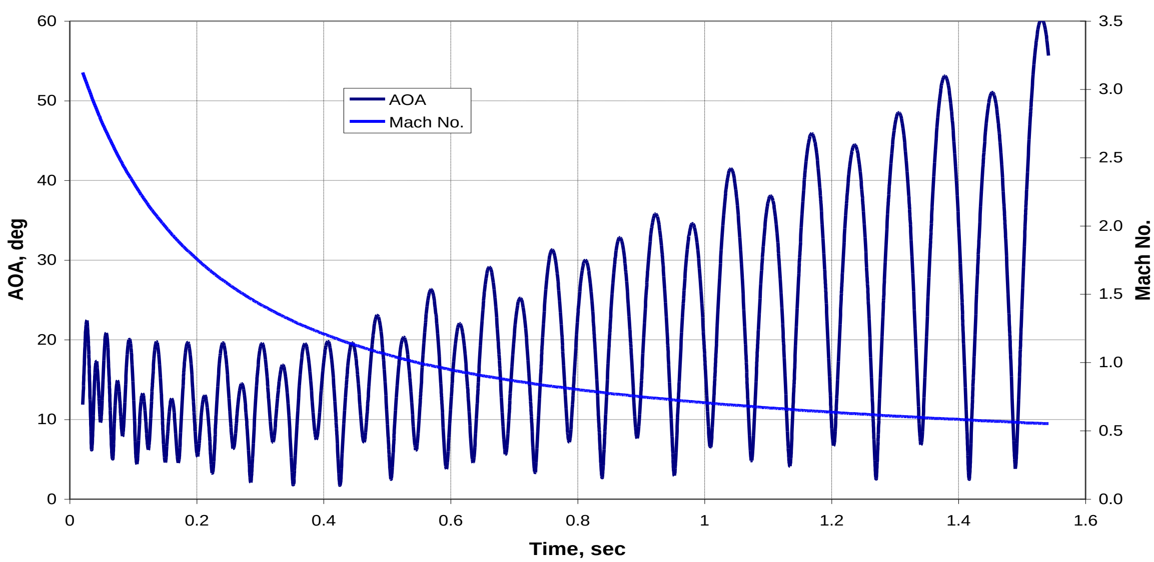


Figure 29. Resulting flight motion with 15-degree angle of attack at launch.

7. CONCLUSION

Artificial yaw induction during free-flight experiments is a technical aspect often taken for granted and almost always necessary for aerodynamics determination. It is used for two reasons: to produce a set of shots at varying yaw levels to characterize the nonlinear behavior of aerodynamic coefficients with respect to yaw, and to increase the accuracy of the fitted data. Over the years, several yaw-induction techniques have been used to increase the initial disturbances. Early techniques included shooting through a high-density gas-filled tube, notching the muzzle end of the launcher, and putting plates near the muzzle to cause asymmetric flow upon exit. More recently, more dependable and repeatable techniques have been developed, including asymmetric modified muzzle brakes, fabricated muzzle devices, asymmetric sabot methods, and deflection techniques.

All of these techniques have had some success; however, quite often an approach that succeeds for one gun caliber or experimental configuration does not work for the next. Furthermore, calibration of a particular technique for a particular launcher and projectile system is still required due to a lack of applicable modeling techniques, but must be within budget and time constraints. This paper can serve as a guide to which techniques might work for a particular gun caliber or situation. The data included in the examples provided may also serve to reduce the amount of yaw-induction calibration for similar flight experiments. Cautionary considerations with regard to modified muzzle brake techniques are cited, such as the potential for large transverse velocities that can damage indoor facilities, and large transverse loads applied at the muzzle that can produce gun tube torque that can potentially damage gun mounts and recoil systems.

Two final yaw induction concepts are worth noting but are outside the overall scope of this paper. First, Murphy [20] described a yaw-induction technique that required the projectile to be eccentrically ballasted by the use of mass imbalance. This approach would be an option only if internal projectile alterations are possible based on geometry considerations and program requirements. Second, as onboard instrumentation systems become more common for advanced aeroballistic development programs, generating an instantaneous yaw event several times along the trajectory may be a particularly fruitful application of yaw induction. Such a system might involve thrusters or retractable canards to apply an angular impulse or disturb the airflow to excite pitching and yawing motion. Once the disturbance is removed, the projectile will naturally damp out. This would allow the aerodynamics to be gathered at several Mach numbers during a single flight. The number of rounds/experimental shots required to get the same amount of data would be reduced, thereby saving on range costs. Such onboard systems are being developed for course-corrected projectiles but may be suitable solely for the purpose of yaw induction if the cost is low enough.

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